

Ionic Polymer-Metal Composites (IPMC) As Biomimetic Sensors and Actuators

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ABSTRACT

This paper discusses a number of recent findings in connection with ion-exchange polymer-noble metal composites (IPMC) as biomimetic sensors and actuators. These smart composites exhibit characteristics of both actuators and sensors. Strips of these composites can undergo large bending and flapping displacement if an electric field is imposed across their thickness. Thus, in this sense they are large motion actuators. Conversely by bending the composite strip, either quasi-statically or dynamically, a voltage is produced across the thickness of the strip between the two conducting electrodes attached. Thus, they are also large motion sensors. The output voltage can be calibrated for a standard size sensor and correlated to the applied loads or stresses. They can be manufactured and cut in any size and shape and in particular in the form of micro sensors and micro actuators for MEMS applications. In this paper first the sensing capability of these materials is reported. The preliminary results show the existence of a linear relationship between the output voltage and the imposed displacement for almost all cases. Furthermore, the ability of these ionic polymer-metal composites as large motion actuators and robotic manipulators is presented. Several muscle configurations are constructed to demonstrate the capabilities of these IPMC actuators. This paper further identifies key parameters involving the vibrational and resonance characteristics of sensors and actuators made with IPMC's. When the applied signal frequency is varied, so does the displacement up to a point where large deformations are observed at a critical frequency called resonant frequency where maximum deformation is observed. Beyond which the actuator response is diminished. A data acquisition system was used to measure the parameters involved and record the results in real time basis. Furthermore, reported in this paper are load characterizations of such active polymer composites made with a noble metal such as platinum. The results showed that these actuators exhibit good force to weight characteristics in the presence of low applied voltages. Finally, reported are the cryogenic properties of these muscles for possible use by NASA in a harsh outer space environment of few Torrs and temperatures of the order of -140 degrees Celsius. These muscles are shown to work quite well in such harsh cryogenics environment and thus present a great potential as sensors and actuators that can operate at cryogenic temperatures.

Keywords: Ionic Polymer-Metal Composite Sensor, Soft Actuator, Artificial Muscles, Biomimetic Sensor, Vibrations, Resonance.

1. INTRODUCTION

Ion-exchange polymer-metal composites (IPMC) are highly active actuators that show very large deformation in the presence of low applied voltage and exhibit low impedance. They operate best in a humid environment and can be made as a self-contained encapsulated actuators to operate in dry environments as well. They have been modeled as both capacitive and resistive element actuators that behave like biological muscles and provide an attractive means of actuation as artificial muscles for biomechanics and biomimetics applications. Grodzinsky¹, Grodzinsky and Melcher^{2,3} and Yannas, Grodzinsky and Melcher⁴ were the first to present a plausible continuum model for electrochemistry of deformation of charged polyelectrolyte membranes such as collagen or fibrous protein and were among the first to perform the same type of experiments on animal collagen fibers essentially made of charged natural ionic polymers and were able to describe the results through electro-osmosis phenomenon. Kuhn⁵ and Katchalsky⁶, Kuhn, Kunzle, and Katchalsky⁷, Kuhn, Hargitay, and Katchalsky⁸, Kuhn, and Hargitay⁹, however, should be credited as the first investigators to report the ionic chemomechanical deformation of polyelectrolytes such as polyacrylic acid (PAA), polyvinyl chloride (PVA) systems. Kent, Hamlen and Shafer¹⁰ were also the first to report the electrochemical transduction of PVA-PAA polyelectrolyte system. Recently

revived

interest in this area concentrates on artificial muscles which can be traced to Shahinpoor and co-workers and other researchers^{11-14, 22-53}, Osada¹⁵, Oguro, Asaka and Takenaka¹⁶, Asaka, Oguro, Nishimura, Mizuhata and Takenaka¹⁷, Guo, Fukuda, Kosuge, Arai, Oguro and Negoro¹⁸, De Rossi, Parrini, Chiarelli and Buzzigoli¹⁹ and De Rossi, Domenici and Chiarelli²⁰. More recently De Rossi, Chiarelli, Osada, Hasebe, Oguro, Asaka, Tanaka, Brock, Shahinpoor, Mojarrad¹¹⁻⁶⁹ have been experimenting with various chemically active as well as electrically active ionic polymers and their metal composites as artificial muscle actuators.

Essentially polyelectrolytes possess many ionizable groups on their molecular chain. These ionizable groups have the property of dissociating and attaining a net charge in a variety of solvent media.. According to Alexanderowicz and Katchalsky²¹ these net charge groups which are attached to networks of macromolecules are called polyions and give rise to intense electric fields of the order of 10^{10} V/m. Thus, the essence of electromechanical deformation of such polyelectrolyte systems is their susceptibility to interactions with externally applied fields as well as their own internal field structure. In particular if the interstitial space of a polyelectrolyte network is filled with liquid containing ions, then the electrophoretic migration of such ions inside the structure due to an imposed electric field can also cause the macromolecular network to deform accordingly. Shahinpoor^{18,22,25,26,28,29,31-,36} and Shahinpoor and co-workers^{21,23,24,27,30} have recently presented a number of plausible models for micro-electro-mechanics of ionic polymeric gels as electrically controllable artificial muscles in different dynamic environments. The reader is referred to these papers for the theoretical and experimental results on dynamics of ion-exchange membranes -platinum composite artificial muscles.

2-BIOMIMETIC SENSING CAPABILITY OF IPMC

Investigations of the use of ion-exchange-membrane materials as sensors can be traced to Sadeghipour, Salomon, and Neogi⁵⁸ where they used such membranes as a pressure sensor/damper in a small chamber which constituted a prototype accelerometer. However, it was Shahinpoor³⁹ who first discussed the phenomenon of flexoelectric effect in connection with dynamic sensing of ionic polymeric gels. In this paper the focus is on application of the IPMC sensor on quasi-static or dynamic displacement sensing where the response of the sensor against large imposed displacements was investigated. To get a better understanding of the mechanism of sensing, more explanation must be given about the nature of the ionic polymers in general.

As shown in Figures 1 and 2, IPMC strips generally bend towards the anode and if the voltage signal is reversed they also reverse their direction of bending.

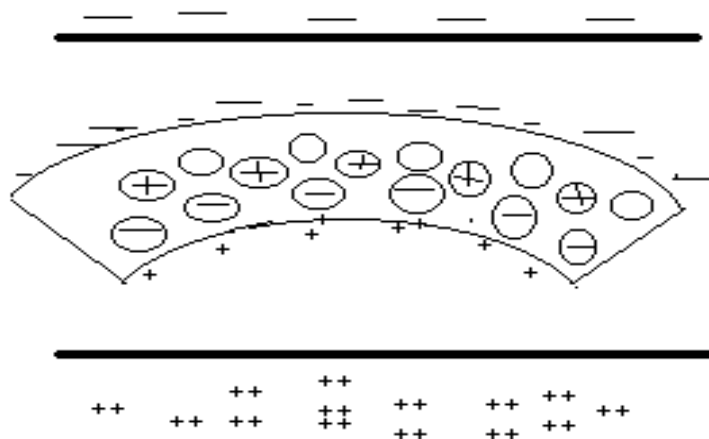


Figure 1. General redistribution of charges in an ionic polymer due to an imposed electric field.

Conversely by bending the material, shifting of mobile charges become possible due to imposed stresses. Consider Figure 2 where a rectangular strip of the composite sensor is placed between two electrodes. When the composite is bent a stress gradient is built on the outer fibers relative to neutral axis (NA). The mobile ions therefore will shift toward the favored region where opposite charges are available. The deficit in one charge and excess in the other can be translated into a voltage gradient which is easily sensed by a low power amplifier.

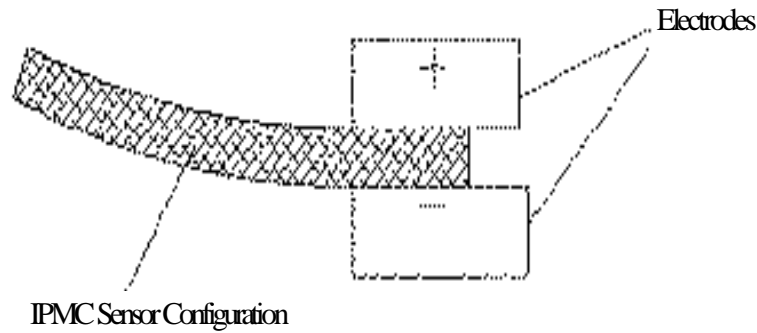


Figure 2. Simple IPMC sensor placed between two electrodes.

2.1-Quasi- Static Sensing

The experimental results showed that a linear relationship exists between the voltage output and imposed quasi-static displacement of the tip of the IPMC sensor as shown in Figure 3. The experimental set up was such that the tip of the cantilevered IPMC strip as shown in Figure 2 was mechanically moved and the corresponding output voltage was recorded. The results are shown in Figure 3.

Sensor Response (+ Displacement) Membrane Face Down

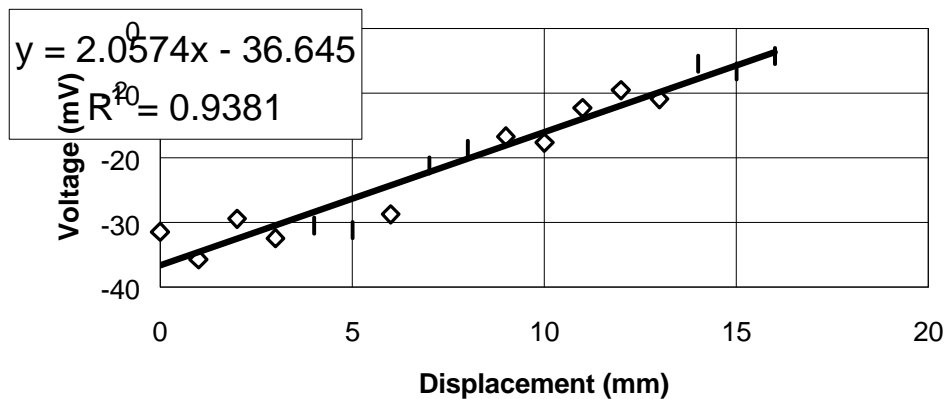


Figure 3. Inverted IPMC film sensor response for positive displacement input.

2.2-Dynamic Sensing

When strips of IPMC are dynamically disturbed by means of a dynamic impact or shock loading, a damped electrical response is observed as shown in Figure 4. The dynamic response was observed to be highly repeatable with a fairly high band width to 100's of HZ. This particular property of IPMC's may find a large number of applications in large motion sensing devices for a variety of industrial applications. Since these muscles can also be cut as small as one desires, they present a tremendous potential to micro-electro-mechanical systems (MEMS) sensing and actuation applications.

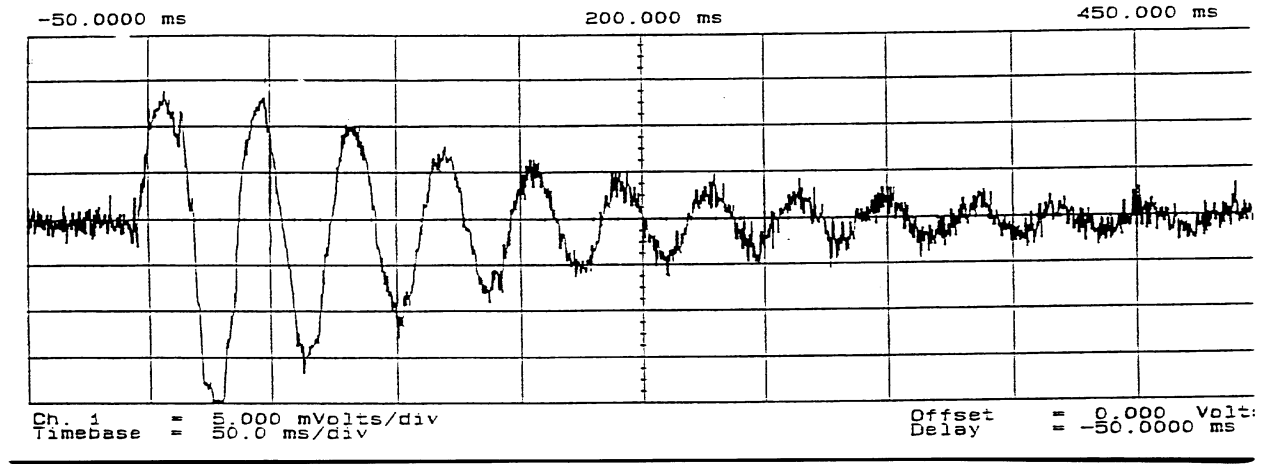


Figure 4- Dynamic sensing response in the form of output voltage of strips (40mmx5mmx0.2mm) of IPMC subject to a dynamic impact loading as a cantilever.

3-BIOMIMETIC ACTUATION PROPERTIES OF IPMC's

3.1- General Considerations

As mentioned before, IPMCs are large motion actuators that operate under a low voltage compared to other actuators such as piezoceramics or shape memory alloys. Table 1 shows a comparison between the capability of IPMC materials and both electroceramics and shape memory alloys. As shown in Table 1, IPMC materials are lighter and their potential striction capability can be as high as two orders of magnitude more than EAC materials. Further, their response time is significantly higher than Shape Memory Alloys (SMA). They can be designed to emulate the operation of biological muscles and they have unique characteristics of low density as well as high toughness, large actuation strain constant and inherent vibration damping.

TABLE 1: Comparison of the properties of IPMC, SMA and EAC

Property	Ionic polymer-Metal Composites (IPMC)	Shape Memory Alloys (SMA)	Electroactive Ceramics (EAC)
Actuation displacement	>10%	<8% short fatigue life	0.1 - 0.3 %
Force (MPa)	10 - 30	about 700	30-40
Reaction speed	μ sec to sec	sec to min	μ sec to sec
Density	1- 2.5 g/cc	5 - 6 g/cc	6-8 g/cc
Drive voltage	4 - 7 V	NA	50 - 800 V
Power consumption	watts	watts	watts
Fracture toughness	resilient, elastic	elastic	fragile

These muscles are manufactured by a unique chemical process in which a noble metal is deposited within the molecular network of the base ionic polymer. One of the interesting properties of IPMC artificial muscles is its ability to absorb large amounts of polar solvents, i.e. water. Platinum, Pt, metal ions, which are dispersed through out the hydrophilic regions of the polymer, are subsequently chemically reduced to the corresponding metal atoms. This results-in the formation of dendritic type electrodes. In Figure 5, scanning electron micrographs are shown in two magnifications, with an order of magnitude difference. On the left, a view is give of the edge of an electroded muscle, the Pt metal covers each surface of the film with some of the metal penetrating the subsurface regions of the material. A closer view with x10 magnification is shown in Figure 5 on the right.

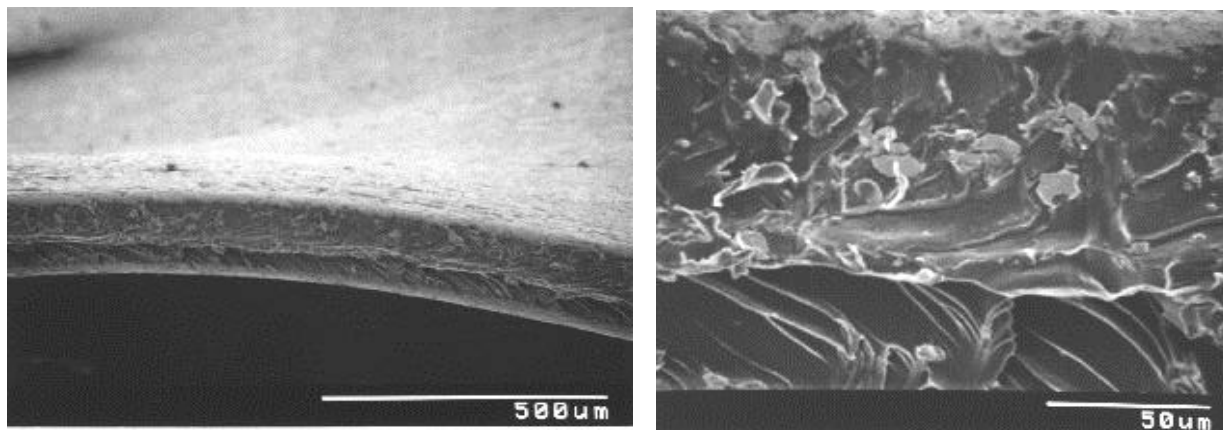


Figure 5: Scanning Electron Micrographs of the structure of IPMC

When an external voltage of 2 volts or higher is applied on a IPMC film, it bends towards the anode. An increase in voltage level (up to 6 or 7 volts) causes a larger bending displacement. When an alternate voltage is applied, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Lower frequencies (down to 0.1 or 0.01 Hz) lead to higher displacement (approaching 25mm). Thus, the movement of the muscle is fully controllable by the applied electrical source. The muscle performance is also strongly dependent on the water content which serves as an ion transport medium and the dehydration rate gradient across the film leads to a pressure difference. The frequency dependence of the ionomer deflection as a function of the applied voltage is shown in Figure 6. A single film was used to emulate a miniature bending arm that lifted a mass weighing a fraction of a gram. A film-pair weighing 0.2-g was configured as a linear actuator and using 5V and 20 mW successfully induced more than 11% contraction displacement. Also, the film-pair displayed a significant expansion capability, where a stack of two film-pairs 0.2-cm thick expanded to about 2.5 cm wide (see Figure 7).

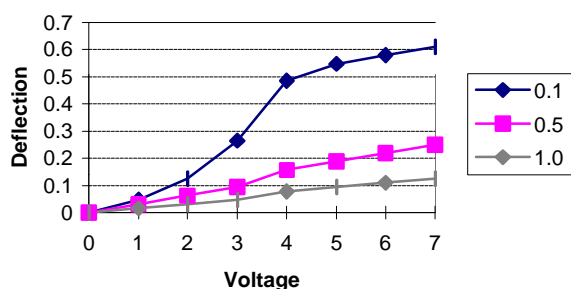


Figure 6: The deflection of a IPMC strip as a function of the frequency (0.1, 0.5 and 1 Hz) and the applied voltage.

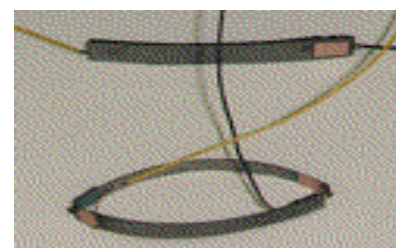


Figure 7: IPMC film-pair in expanded mode. A reference pair (top) and an activated pair (bottom).

3.2- Muscle actuators for soft robotic applications

IPMC films have shown remarkable displacement under a relatively low voltage drive, using a very low power. However these ionomers have demonstrated a relatively small force actuation capability. Since the IPMC films are made of a relatively strong material with a large displacement capability, we investigated their application to emulate fingers. In Figure 8, a gripper is shown that uses IPMC fingers in the form of an end-effector of a miniature low-mass robotic arm.

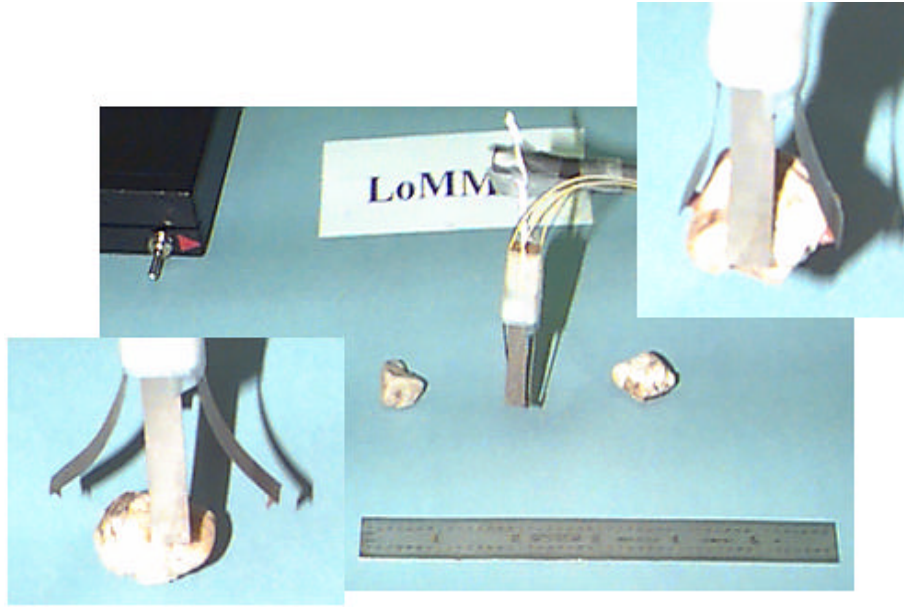


Figure 8: An end-effector gripper lifting 10.3-g rock under 5-V, 25-mW activation using four 0.1-g fingers made of IPMC's.

The fingers are shown as vertical gray bars and the electrical wiring, where the films are connected back-to-back, can be seen in the middle portion of Figure 8. Upon electrical activation, this wiring configuration allows the fingers to bend either inward or outward similar to the operation of a hand and thus close or open the gripper fingers as desired. The hooks at the end of the fingers represent the concept of nails and secure the gripped object that is encircled by the fingers.

So-far, multi-finger grippers that consist of 2- and 4-fingers were produced, where the 4-finger gripper shown in Figure 8 was able to lift 10.3-g. This gripper prototype was mounted on a 5-mm diameter graphite/epoxy composite rod to emulate a light weight robotic arm. This gripper was driven by 5 volts square wave signal at a frequency of 0.1 Hz to allow sufficient time to perform a desirable demonstration of the capability of the Gripper -- opening the gripper fingers, bringing the gripper near the collected object, closing the fingers and lifting an object with the arm. The demonstration of this gripper capability to lift a rock was intended to pave the way for a future application of the gripper to planetary sample collection tasks (such as Mars Exploration) using ultra-dexterous and versatile end-effector.

3.3- Linear and Platform type actuators

For detailed dynamics description and analysis of the dynamic theory of ionic polymeric gels the reader is referred to Shahinpoor and co-workers^{11-14,22-70}. Since ionic polyelectrolytes are for the most part three dimensional network of macromolecules cross-linked nonuniformly, the concentration of ionic charge groups are also nonuniform within the polymer matrix. Therefore the mechanism of bending is partially related to migration of mobile ions within the network due to imposition of an electric field as shown in Figure 1. However, recent investigation by the author and his co-workers point

to a stronger effect due to surface charge interaction which will be reported later. Figure 9 depicts the bending deformation of a typical strip with varying electric field, while Figure 10 displays the variation of deformation with varying frequency of alternating electric field.

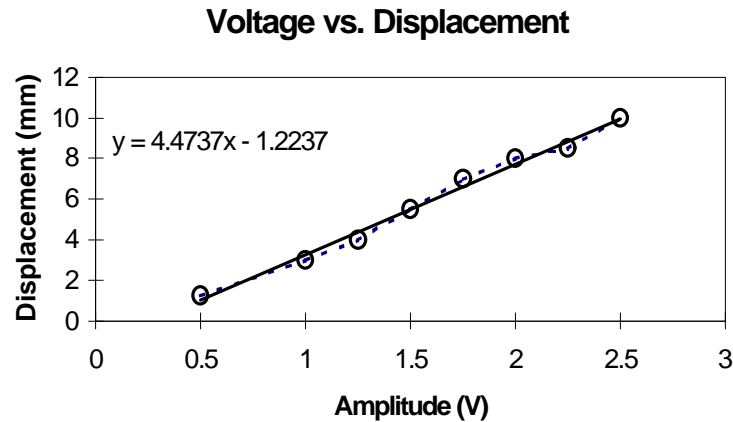


Figure 9-Bending Displacement versus Voltage for a typical IPMC strip of 5mmx0.20mmx20mm under a frequency of 0.5Hz.

Based on such dynamic deformation characteristics, linear and platform type actuators can be designed and made dynamically operational. These types of actuators are typically shown in Figure 11.

4-LARGE AMPLITUDE VIBRATIONAL RESPONSE OF IPMC's

4.1-General Considerations

Strips of IPMC were used to study their large amplitude vibration characteristics. The IPMC strips were chemically composited with Platinum. A small function generator circuit was designed and built to produce approximately $\pm 4.0V$ amplitude alternating wave at varying frequency. In order to study the feasibility of using IPMC artificial muscles as vibration damper, a series of muscles made from IPMC's were cut into strips and attached either end-to-end or to one fixed platform and another movable platform in a cantilever configuration. By applying a low voltage the movement of the free end of the beam could be calibrated and its response measured, accordingly. Typical data for the frequency-dependence of amplitude of lateral oscillations of the muscle strips subjected to alternating voltages of various forms such as sinusoidal, rectangular, saw-tooth or pulsed is presented. Furthermore, additional data is presented on static deformation of the strip with voltage as well as the frequency dependence of deflection-voltage curves.

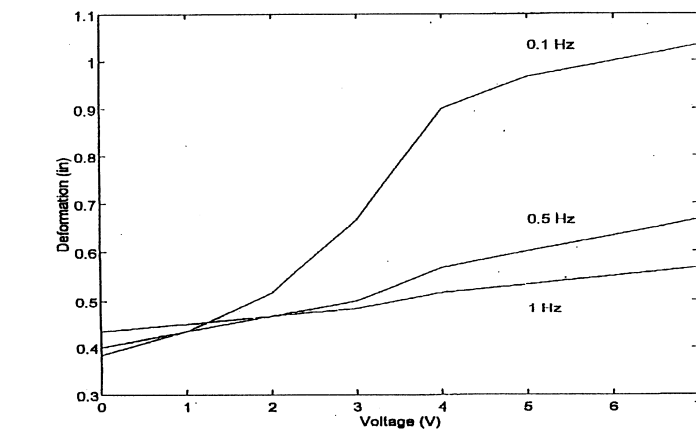


Figure 10-Frequency dependence of bending deformation of IPMC composite muscles

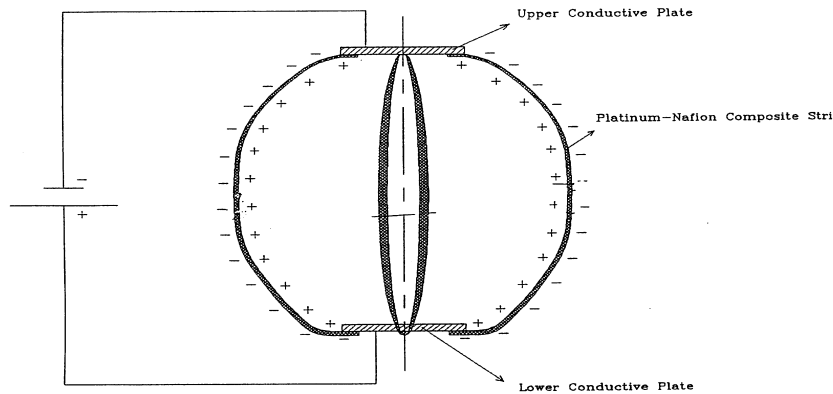


Figure 11- A typical linear-type robotic actuators made with IPMC legs

4.2--EXPERIMENTAL OBSERVATIONS

A 15cmx15cm piece of a typical ion-exchange membrane such as Nafion 117 (Du Pont Company) was chemically treated with platinum to produce the IPMC artificial muscle. Then typical strips of about 2-4cmx4-6mm of membrane composite was cut and completely swollen in a suitable solution such as water or alcohol to swell. The IPMC muscle strip typically weighed 0.1-0.4 grams and its thickness measured about 0.2mm after platinum was deposited on and within its two surfaces and was swollen in water. The strip was then held by a clamping setup between two platinum plate terminals which were wired to a signal amplifier and generator apparatus driven by Labview software through an IBM compatible PC containing an analog output data acquisition board. The amplifier (Crown model D-150A) was used to amplify the signal output of a National Instrument data acquisition card (AT-AO-10). A software was written to produce various waveforms such as sinusoid, square, triangular and saw tooth signals at desired frequencies up to 100 Hz and amplitudes up to 10 volts. When a low voltage was applied, the membrane composite bent toward the anode side each time. So by applying an alternating signal we were able to observe alternating bending of the actuator that followed the input signal very closely up to 35 Hz of frequency. At voltages higher than 2.0 volts, the electrolysis of water in the composite was observed which led to degradation of displacement output of the actuator. Another factor affecting IPMC strip performance was the dehydration. Water acts as the single most important element for the composite bending by sequentially moving within the composite depending on the polarity of the electrodes. The side facing the anode dehydrated faster than the side facing the cathode leading to a differential stresses which ultimately leads to bending of the composite. So, prior to each experiment, the composite was completely swollen in water. The displacement of the free end of a typical 2cmx4mm composite membrane was then measured for frequency range of 0.1-35 Hz for sinusoid input voltage at 2.0 volts amplitude (Figure 12).

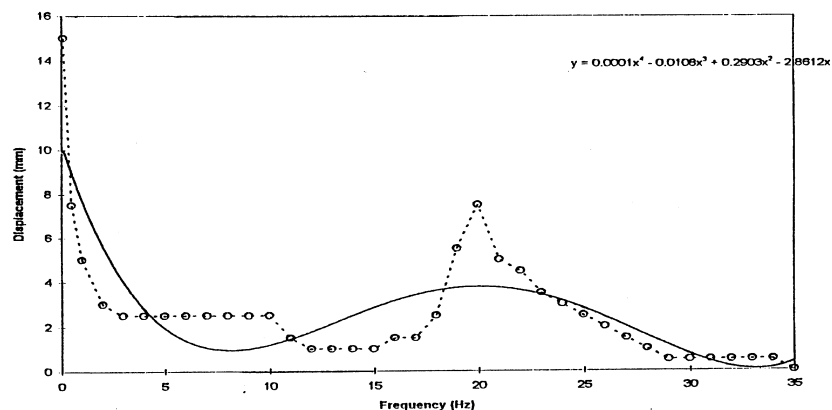


Figure 12- Amplitude of displacement versus the imposed frequency for a voltage of 2 volts for a 2cmx4mmx0.2mm sample.

Resonance was observed at about 20 Hz frequency where the associated displacement was observed to be 7.5mm. It should be noted that as the actuator dehydrated the resonance frequency and maximum displacement varied accordingly. By encapsulating the strips in a plastic membrane such as Saran, the deterioration in the amplitude of oscillation decreased with time. However, the initial amplitude of oscillation for the same level of voltage was smaller than the unwrapped case due to increased rigidity of the strip. For our sample actuator the resonance occurred in the frequency range of 12 to 28 Hz for various swelling ratio.

Based on such dynamic deformation characteristics, noiseless swimming robotic structures as shown in Figure 13 and cilia assembly-type robotic worlds, similar to coral reefs, as shown in Figure 14, were constructed and tested for collective vibrational dynamics. Furthermore, wing flapping flying machines, schematically shown in Figure 15, can be equipped with these muscles.

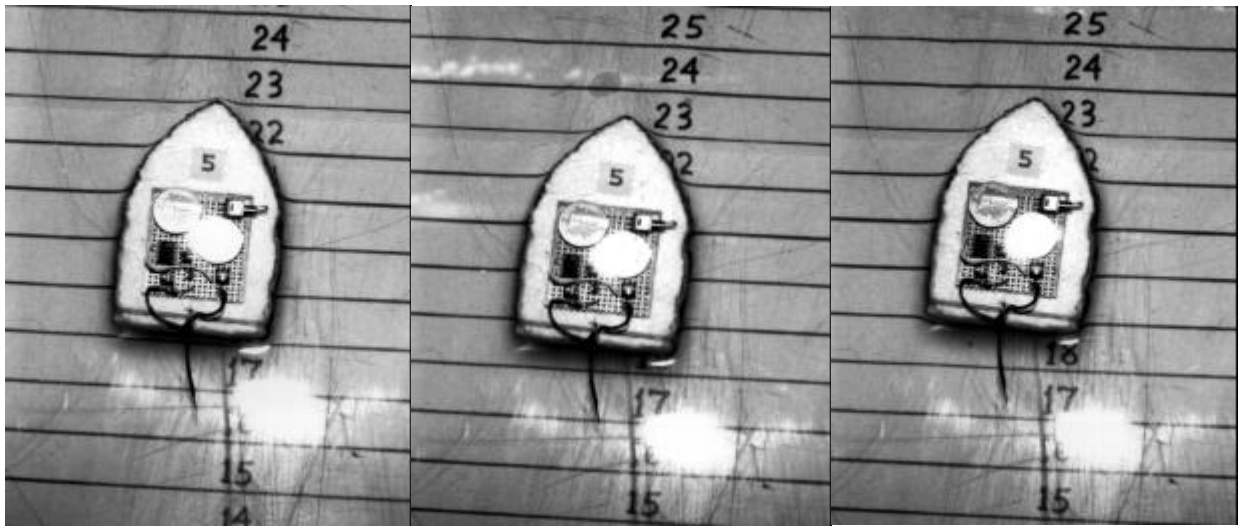


Figure 13. Robotic swimmer with muscle undulation frequency of 5 Hz (frame time interval, 1/3 second).



Figure 14-Cilia-Type assembly of IPMC-Pt Muscles Simulating Collective Dynamic Vibrational Response Similar to Coral Reefs and could create anti-biofouling surfaces

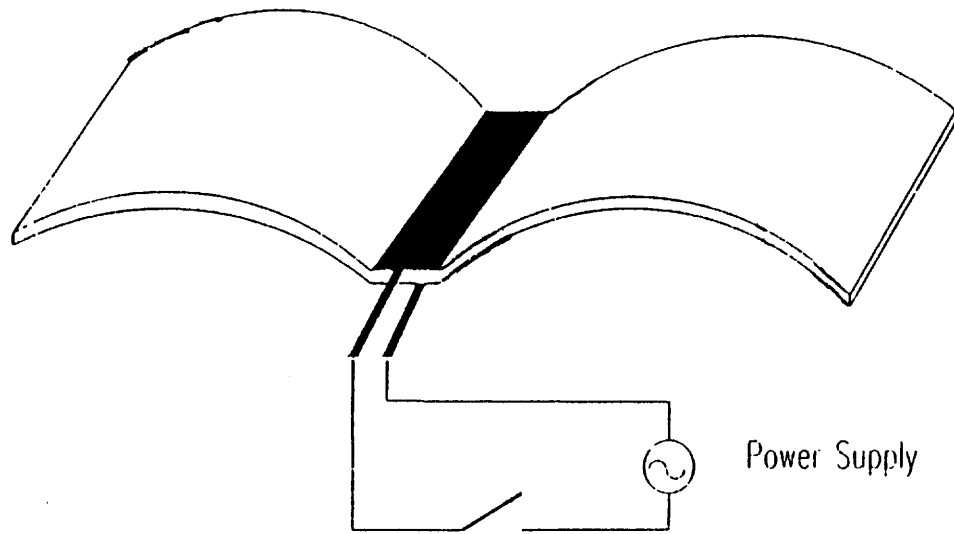


Figure 15-Wing-flapping flying machines design depicted schematically.

5-LOAD AND FORCE CHARACTERIZATION OF IPMC's

In order to measure the force generated by strips of these muscles in a cantilever form an experimental set up was designed using a load cell. A load cell (Transducer Techniques, model GS-30, 30 grams capacity) and corresponding signal conditioning module (Transducer Techniques, model TMO-1) together with a power supply was setup and connected to a PC-platform data acquisition and signal generation system composed of a 12-bit analog output board (National Instrument AT-AO-10) and a 16-bit multi-input-output board (National Instrument AT-MIO-16XE-50). A Nicolet scope was used to monitor the input and output waveform. Labview™ software was used to write a program to generate various waveform such as sinusoid, square, saw tooth, and triangular signals at desired frequency and amplitude. The effective length of the membrane was 10mm. This made the effective weight of the muscle producing a force to be about 20 milligrams. The resulting graphs were then adjusted for initial noise and pre-load and plotted over 5 seconds period (2.5 cycles). The force capability of these muscles, on the average was measured to be about 400 N/Kgm indicating that these muscles can lift almost 40 times their own weight. Figures 16 depict such general trends.

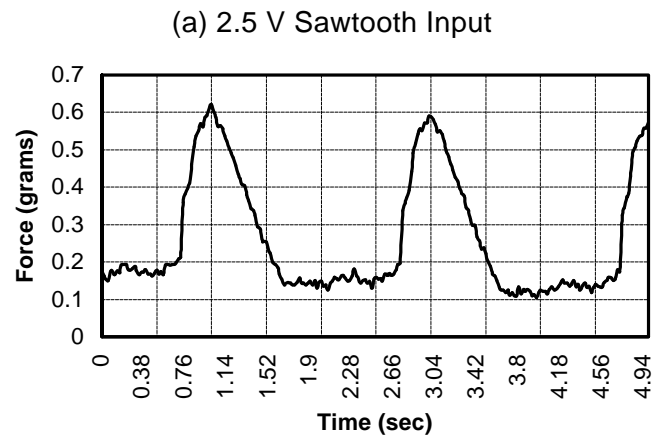
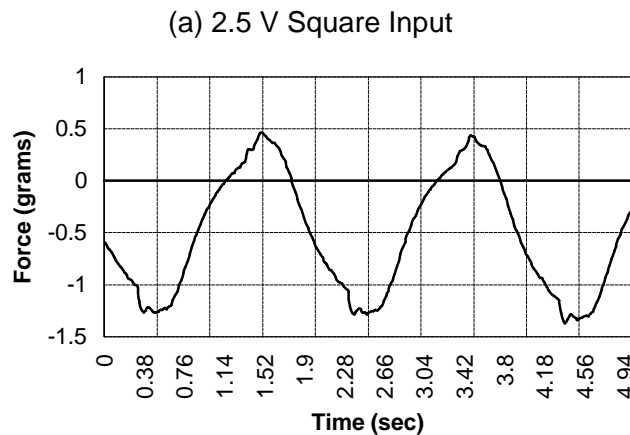


Figure 16. IPMC actuator response for square and saw tooth wave input at 2.5 Volts rms.

6-CRYOGENIC PROPERTIES OF IPMC ARTIFICIAL MUSCLES

In this section are reported a number of recent experimental results pertaining to the behavior of ionic polymer metal composites (IPMC) under low pressure (few Torr) and low temperatures (-140 degrees Celsius). These experimental results have been obtained in a cryogenic chamber at JPL as well as a cryogenic chamber at the Artificial Muscles Research Institute at UNM. The interest at JPL was to study the actuation properties of these muscles in a harsh space environment such as one Torr of pressure and -140 degrees Celsius temperature. While at UNM the electrical properties, sensing capabilities as well as actuation properties of these muscles were tested in an atmospheric pressure chamber with a low temperature of -80 degrees Celsius. The general results

are that these materials are still capable of sensing and actuation in such harsh conditions as the following Figures 17 through 24 display. Furthermore, these IPMC artificial muscles become less conductive, i.e., their electrical resistance increases with decreasing temperature. This result appears to defy the generally accepted fact that resistance of metallic conductors increases/decreases with increasing/decreasing temperature, respectively.

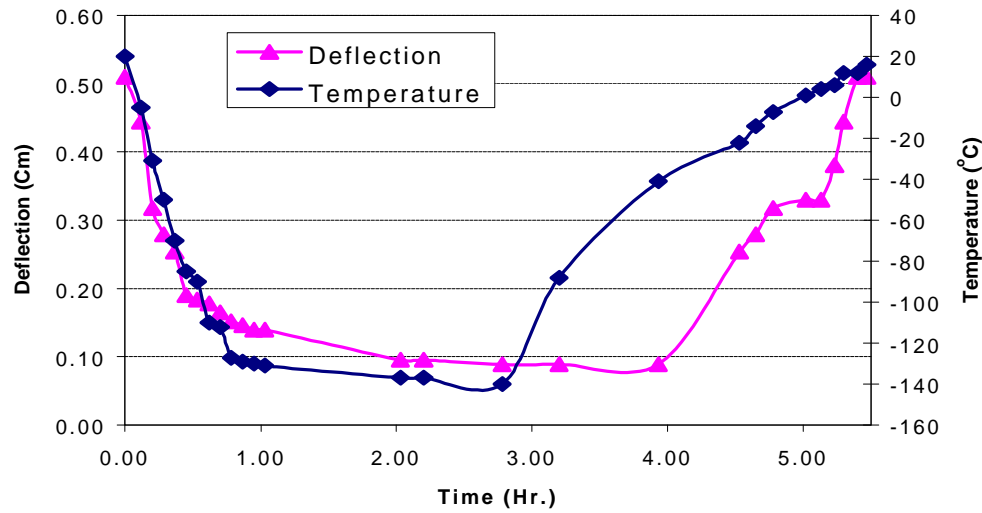


Figure 17- Deflection characteristics of IPMC as a function of time and temperature

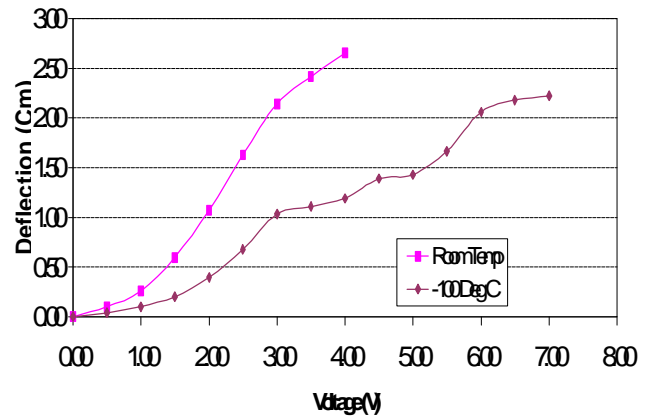
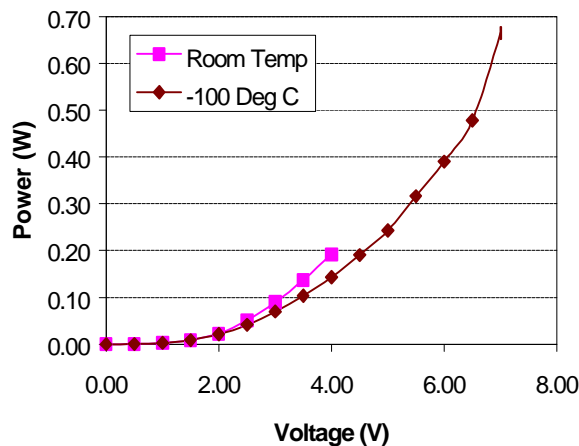
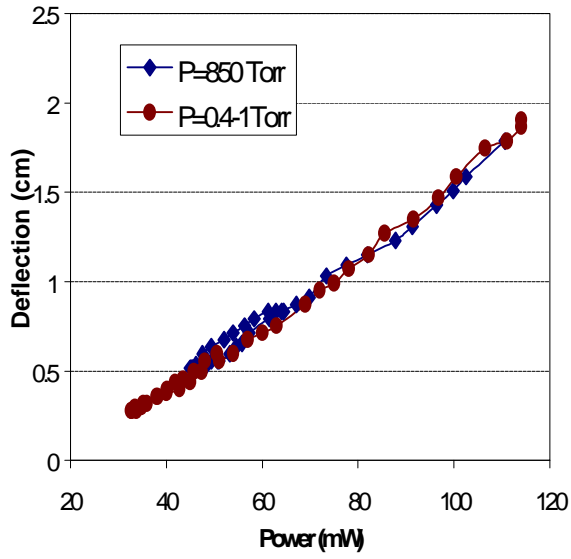
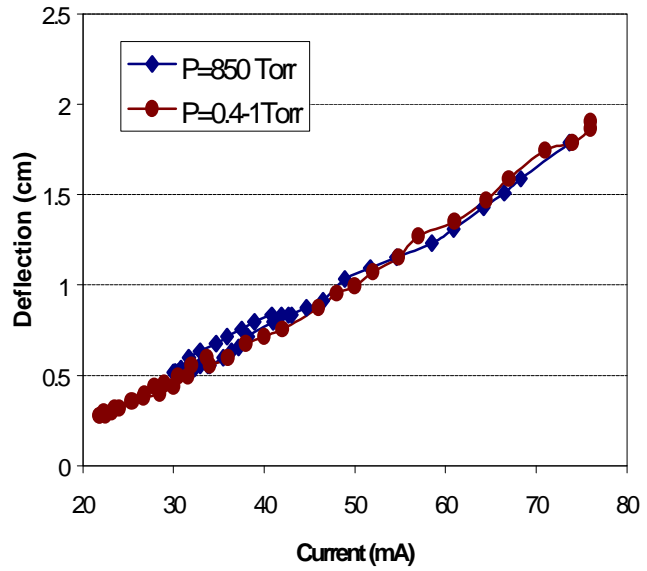


Figure 18: Power consumption of the IPMC strip bending actuator as a function of activation voltage.

Figure 19: Deflection of the bending IPMC strip as function of voltage

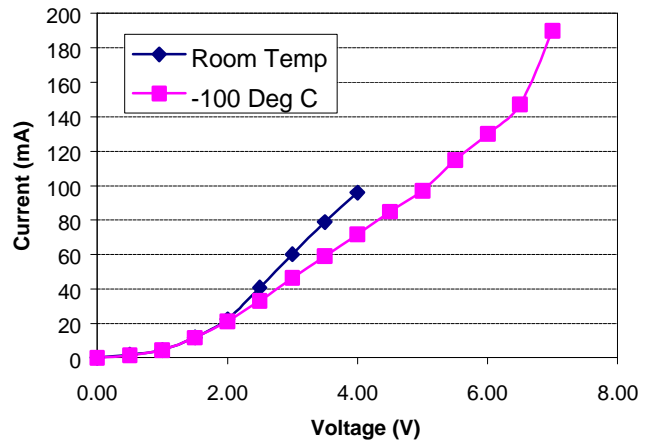
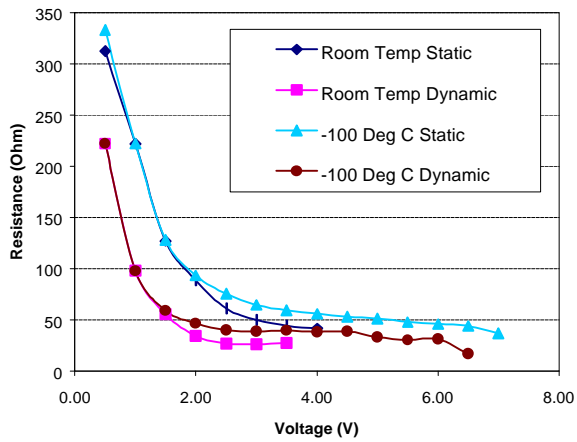


a. View of the deflection vs. power



b. View of the deflection vs. current

Figure 20- Temperature changes in the range of 23 to -120°C versus power and current under a constant voltage of 3 volts
And a frequency of 0.1-Hz.



(a)-IPMC strip static (V/I) and dynamic (V/I) resistance at various temperature.

(b)-The relation between voltage and current for an IPMC strip that was exposed to RT and to -100°C.

Figure 21- Effect of temperature on the electrical resistance.

Figure 21 (a) clearly shows a remarkable trend which is opposite to the normal trend of resistance-temperature variations in conductors. The graph is showing that as the temperature decreases in IPMC artificial muscles the resistance increases . For any given temperature, there is a range of linear response of V vs. I, which indicates a close to a pure resistor response. This rather remarkable effect is presently under study. However, one plausible explanation is that the colder the temperature the less active ionic species within the network of IPMC and thus the less ionic current activities. Since current is voltage over the resistance R, i.e., $I=V/R$, thus R has to increase to accommodate the decreasing ionic current due to decreasing temperature. Figures 22 , 23 and 24 show the relationship between the temperature, voltage , current, power and displacement in typical IPMC strips.

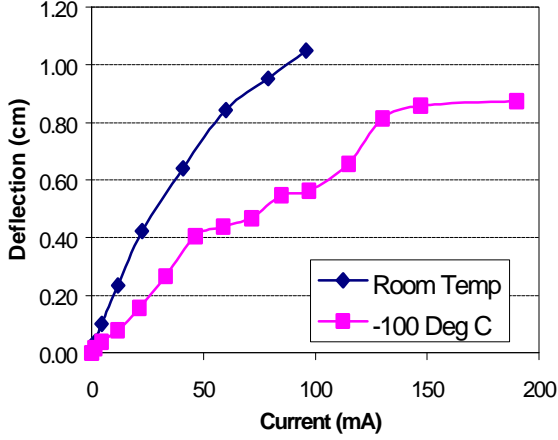


Figure 22-The relation between the current and the deflection for an IPMC strip that was exposed to room temperature and to -100°C.

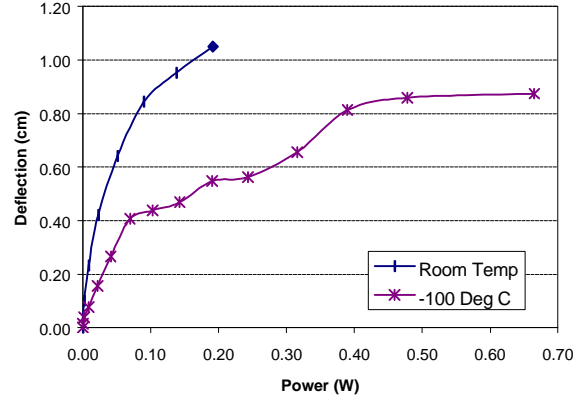


Figure 23-The relation between the power and the deflection for an IPMC strip that was exposed to room temperature and to -100°C.

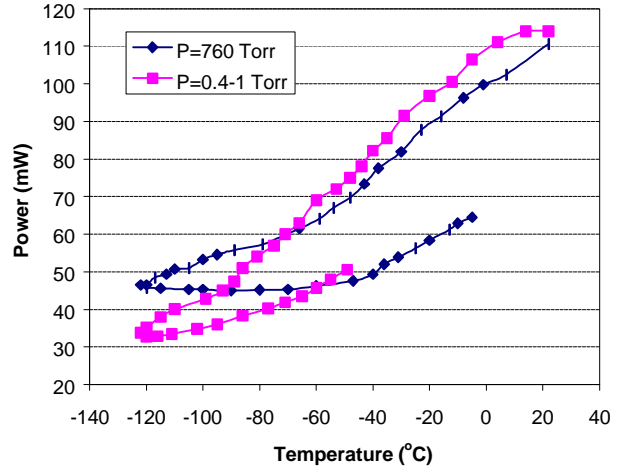
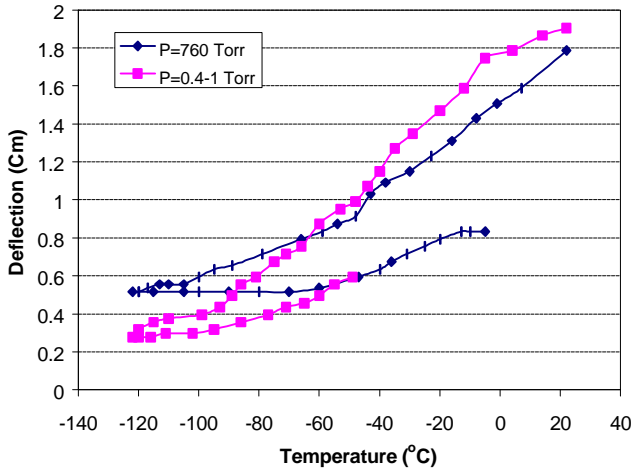


Figure 24-Deflection and power consumption of the IPMC muscle as a function of temperature with pressure as a parameter. $V_{peak}=3$ V, $Freq=0.1$ Hz.

7-CONCLUSIONS

Highly Dynamic sensing characteristics of IPMC strips were remarkable in accuracy and repeatability and were found to be superior to existing motion sensors and micro sensors. A new type of soft actuator and multi-fingered robotic hand were made from IPMC artificial muscles and were found to be quite superior to conventional grippers and multi-fingered robotic hands. The feasibility of designing linear and platform type robotic actuators made with IPMC artificial muscle were presented.. By applying a low voltage the movement of free end of the actuator could be calibrated and its response could be measured, accordingly. The feasibility of designing dynamic vibrational systems of artificial muscles made with IPMC artificial muscle were presented. Our experiments confirmed that these types of composite muscles show remarkable bending displacement that follow input signal very closely. When the applied signal frequency is varied, so did the displacement up to a point where large deformations were observed at a critical frequency called resonant frequency where maximum deformation was observed, beyond which the actuator response was diminished. A data acquisition system

was used to measure the parameters involved and record the results in real time basis. The observed remarkable vibrational characteristics of IPMC-Pt composite artificial muscles clearly point to the potential of these muscles for biomimetics applications such as swimming robotic structures, wing-flapping flying machines, slithering snakes, heart and circulation assist devices, peristaltic pumps and dynamic robotic cilia-worlds. The cryogenic properties of these materials were quite unique. The fact that they still operated at very low temperatures such as -140 degrees Celsius shows their potential as cryogenic sensors and actuators. Their resistance increased with decreasing temperature, a property that is opposite to all metallic conductors.

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